

Observation of the Radiative Decay $D^0 \rightarrow \phi\gamma$

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Abstract

We report the observation of the decay $D^0 \rightarrow \phi\gamma$ with a statistical significance of 5.4σ in 78.1 fb^{-1} of data collected by the Belle experiment at the KEKB e^+e^- collider. This is the first observation of a flavor-changing radiative decay of a charmed meson. The Cabibbo- and color-suppressed decays $D^0 \rightarrow \phi\pi^0$, $\phi\eta$ are also observed for the first time. We measure branching fractions $\mathcal{B}(D^0 \rightarrow \phi\gamma) = [2.60^{+0.70}_{-0.61} (\text{stat.})^{+0.15}_{-0.17} (\text{syst.})] \times 10^{-5}$, $\mathcal{B}(D^0 \rightarrow \phi\pi^0) = [8.01 \pm 0.26 (\text{stat.}) \pm 0.47 (\text{syst.})] \times 10^{-4}$, and $\mathcal{B}(D^0 \rightarrow \phi\eta) = [1.48 \pm 0.47 (\text{stat.}) \pm 0.09 (\text{syst.})] \times 10^{-4}$.

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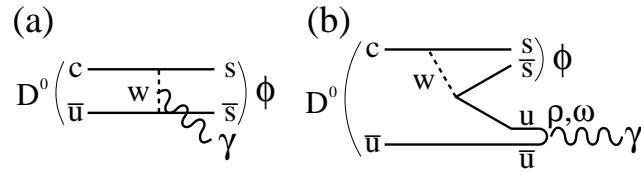


FIG. 1: Decay diagrams for the decay $D^0 \rightarrow \phi\gamma$: (a) short-distance, (b) long-distance process.

Flavor-changing radiative decays of the charmed meson system, $D \rightarrow V\gamma$ where V is a vector meson, have not previously been observed. In the Standard Model, the short-distance contribution to these decays is negligible (the branching fraction from this contribution is predicted to be less than 10^{-8}), and the long-distance contribution due to a vector meson coupling to a photon is expected to be dominant [1, 2]. Examples of short- and long-distance processes for the decay $D^0 \rightarrow \phi\gamma$ are shown in Figure 1. The branching fraction of this mode is expected to lie in the range $(0.04 - 3.4) \times 10^{-5}$ [2, 3]; the current 90% confidence level (C.L.) upper limit from CLEO is $\mathcal{B}(D^0 \rightarrow \phi\gamma) < 1.9 \times 10^{-4}$ [4]. In the B -meson system, where the short-distance contribution to $B \rightarrow X_d\gamma$ (X_d is ρ, ω) decay can be used to measure the CKM matrix element V_{td} , theoretical estimates of the long-distance contribution are also uncertain [5]. Measurement of radiative D meson decays therefore provides an important constraint on the interpretation of $B \rightarrow X_d\gamma$ results.

In this paper, we present the first observation of the $D^0 \rightarrow \phi\gamma$ decay. The analysis is based on 78.1 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance by the Belle detector [6] at the KEKB e^+e^- collider [7]. KEKB is a pair of electron storage rings with asymmetric energies, 3.5 GeV for e^+ and 8 GeV for e^- , and a single interaction point. The Belle detector is a large-solid-angle general purpose spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

According to a Monte Carlo (MC) study, the most important backgrounds to $D^0 \rightarrow \phi\gamma$ are the Cabibbo- and color-suppressed decays $D^0 \rightarrow \phi\pi^0$ and $\phi\eta$, which have not previously been observed. We therefore conduct a search for these decay modes as well. To reduce the combinatorial background, D^0 candidates are combined with π^+ to form D^{*+} candidates. We calculate the difference in invariant mass, $\Delta M = M_{D_{cand}^0\pi^+} - M_{D_{cand}^0}$, and require $143.4 \text{ MeV}/c^2 < \Delta M < 147.4 \text{ MeV}/c^2$.

Charged particle tracks are reconstructed in the SVD and CDC and required to be consistent with originating from the interaction region; the nearest approach of the trajectory to the collision point, which is determined run-by-run, is required to pass $|dr| < 0.5 \text{ cm}$ and $|dz| < 1.5 \text{ cm}$, where dz is taken in the direction of the positron beam and dr is in the plane perpendicular to it. Particle identification (ID) likelihoods for the pion (\mathcal{L}_π) and kaon (\mathcal{L}_K) hypotheses are determined from the ACC response, specific ionization (dE/dx) measurement in the CDC, and the time-of-flight measurement for each track. To identify kaons (pions), we apply a mode-dependent requirement on the likelihood ratio $\mathcal{R} \equiv \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$: a criterion of $\mathcal{R} > 0.6$ ($\mathcal{R} < 0.1$) yields an efficiency of 86% (79%) for kaons (pions).

The rate at which pions (kaons) are misidentified as kaons (pions) under these criteria is 8% (5%). We select ϕ candidates from K^+K^- combinations in the invariant mass range $1.01 \text{ GeV}/c^2 < M_{K^+K^-} < 1.03 \text{ GeV}/c^2$, and use combinations from the mass sidebands (ϕ_{sb}), $0.99 \text{ GeV}/c^2 < M_{K^+K^-} < 1.00 \text{ GeV}/c^2$ and $1.04 \text{ GeV}/c^2 < M_{K^+K^-} < 1.05 \text{ GeV}/c^2$, to estimate the background under the ϕ peak.

Neutral π mesons (π^0) are formed by pairing photons, each with energy $E_\gamma > 50 \text{ MeV}$, and requiring a pair invariant mass within $\pm 16 \text{ MeV}/c^2$ ($\sim 3\sigma$) of the nominal π^0 mass; the photon momenta are then recalculated with a π^0 mass constraint [8]. For $\eta \rightarrow \gamma\gamma$ and $D^0 \rightarrow \phi\gamma$ reconstruction, photon candidates passing $E_\gamma > 50 \text{ MeV}$ are selected if no pairing with any other photon in the event ($E_\gamma > 20 \text{ MeV}$) yields an invariant mass that is consistent with the π^0 mass (the π^0 veto). Otherwise, η meson candidates are formed from pairs of selected photons and required to have an invariant mass within $\pm 40 \text{ MeV}/c^2$ ($\sim 4\sigma$) of the η mass. The photon momenta are then recalculated with an η mass constrained fit [8].

We make the following requirements on laboratory momentum or energy: $P_{\pi^0} > 750 \text{ MeV}/c$ for $D^0 \rightarrow \phi\pi^0$, $P_\eta > 500 \text{ MeV}/c$ for $D^0 \rightarrow \phi\eta$, and $E_\gamma > 450 \text{ MeV}$ for $D^0 \rightarrow \phi\gamma$. The D^* momentum in the e^+e^- center-of-mass is required to satisfy $P_{D^*} > 2.9 \text{ GeV}/c$ for all modes; this criterion is optimised for the selection of $D^0 \rightarrow \phi\gamma$ and is above the kinematic limit for D^* 's produced in B decays at the $\Upsilon(4S)$ resonance. These criteria are determined using MC such that they do not introduce bias for the signal in data.

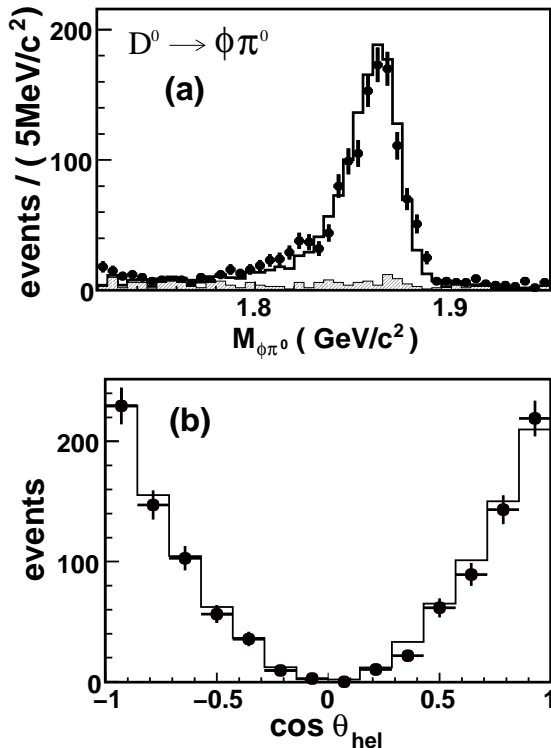


FIG. 2: $D^0 \rightarrow \phi\pi^0$: (a) invariant mass distribution for data (points with errors), combinations of ϕ -sideband and π^0 (shaded histogram), and sideband + MC signal shape, scaled to the result of the fit described in the text (solid histogram); (b) fitted D yield in bins of $\cos \theta_{\text{hel}}$ (points with errors) (θ_{hel} is the ϕ helicity angle) and the MC prediction (histogram).

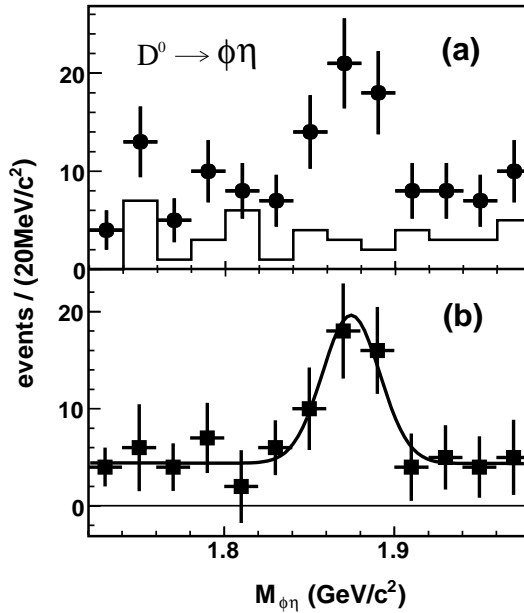


FIG. 3: $D^0 \rightarrow \phi\eta$: (a) invariant mass distribution for data (points with errors) and combinations of ϕ -sideband and η (histogram); (b) background-subtracted distribution, with a fit function described in the text (solid curve).

The reconstructed $M_{\phi\pi^0}$ distribution shows a clear enhancement at the D^0 mass (Figure 2(a)). The distribution from non-resonant $D^0 \rightarrow K^+K^-\pi^0$ decay also peaks at the D^0 mass. Its contribution is evaluated using ϕ -sideband D^0 candidates, constructed from $\phi_{sb}\pi^0$ combinations and found to comprise $3.1 \pm 0.9\%$ of the net D^0 yield. The signal yield is extracted by a χ^2 fit to the sideband-subtracted $M_{\phi\pi^0}$ distribution, assuming an exponential shape for the background and a signal shape developed by the Crystal Ball experiment [9]. We obtain 1254 ± 39 events ($\chi^2/ndf = 25.6/38$). To measure the helicity state, we form the helicity angle θ_{hel} , the angle between the K^+ and D^0 3-momenta in the rest frame of the ϕ meson. Due to the conservation of angular momentum, the distribution in $\cos\theta_{hel}$ is expected to be proportional to $\cos^2\theta_{hel}$ for $D^0 \rightarrow \phi\pi^0$ and $\phi\eta$ decays but proportional to $\sin^2\theta_{hel}$ ($= 1 - \cos^2\theta_{hel}$) for $D^0 \rightarrow \phi\gamma$. The distribution for $\phi\pi^0$ candidates agrees well with the MC expectation (Figure 2(b)). When a $\phi\pi^0$ or $\phi\eta$ decay is reconstructed as a $\phi\gamma$ candidate by missing one photon, the distribution of $\cos\theta_{hel}$ is still close to $\cos^2\theta_{hel}$. The background to $D^0 \rightarrow \phi\gamma$ from $\phi\pi^0/\phi\eta$ decay is thus strongly suppressed by a requirement on θ_{hel} .

The $M_{\phi\eta}$ and ϕ -sideband ($M_{\phi_{sb}\eta}$) distributions are shown in Figure 3(a). We extract the signal yield from the sideband-subtracted $M_{\phi\eta}$ distribution shown in Figure 3(b). The χ^2 fit yields 31.1 ± 9.8 signal events, where Gaussian and first-order polynomial shapes are assumed for the signal and background, respectively. The significance of the signal, taken to be $\sqrt{-2\ln(L_0/L_{best})}$ where L_{best} and L_0 are the maximum likelihood values with the signal floated and fixed to zero, respectively, is 4.4σ .

For the radiative mode, we require $|\cos\theta_{hel}| < 0.4$. A clear peak is observed at the D^0 mass in the $M_{\phi\gamma}$ invariant mass distribution (Figure 4(a)). The signal yield is extracted using the binned maximum likelihood method. The shapes of signal and background from

$D^0 \rightarrow \phi\pi^0$, $\phi\eta$ and $D^+ \rightarrow \phi\pi^+\pi^0$ (feed-down) are obtained by MC simulation. The reliability of the simulation is checked by studying $K_S^0\gamma$ combinations with an invariant mass near the D^0 mass: the process $D^0 \rightarrow K_S^0\gamma$ is forbidden, so any peaking in the signal region must be due to $D^0 \rightarrow K_S^0\pi^0$ and $K_S^0\eta$ events, similar to the feed-down background in this analysis. We observe no peaking. We find similar distributions in data and MC. The feed-down rates are normalized to the observed rates for the source modes, and the systematic uncertainty is due to the uncertainty on the source rates. The shape of the combinatorial background is estimated by fitting a first order polynomial to ϕ -sideband ($\phi_{sb}\gamma$) candidates. The normalization of this contribution is allowed to float in the fit. The extracted yield is $27.6^{+7.4}_{-6.5}$ (stat.) $^{+0.5}_{-1.0}$ (syst.) events. The significance of the signal is 5.4σ .

With the signal region defined as $[1.78 - 1.92]$ GeV/c^2 and the requirement on $\cos\theta_{hel}$ released, the distribution in $\cos\theta_{hel}$ shows an excess of signal over background near $\cos\theta_{hel} \sim 0$ (Figure 4(b)). It is clear that, without the requirement on helicity angle, the feed-down from $D^0 \rightarrow \phi\pi^0$ and $\phi\eta$ is large. Figure 4(c) shows the helicity angle distribution after background subtraction. It is consistent with the $\sin^2\theta_{hel}$ distribution expected for the $D^0 \rightarrow \phi\gamma$ signal.

To minimize systematic uncertainties, we measure the branching fraction as a ratio to

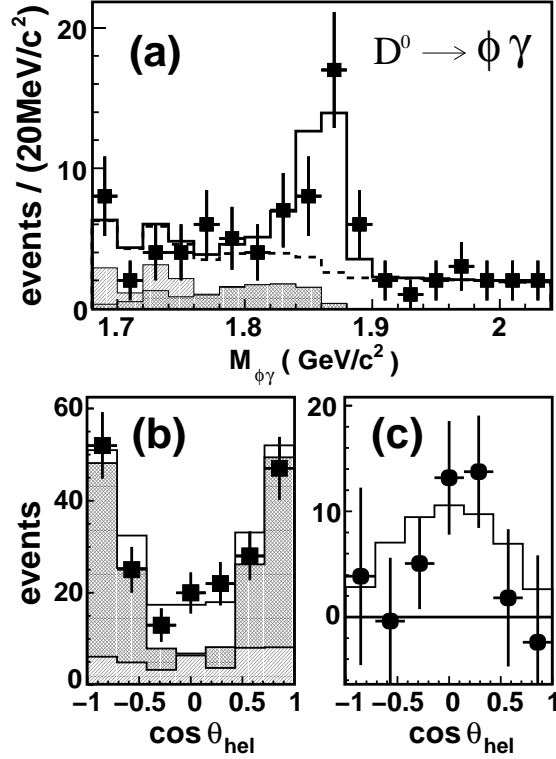


FIG. 4: $D^0 \rightarrow \phi\gamma$: (a) invariant mass distribution for data (points with errors), the fit described in the text (solid histogram), the background component of the fit (dashed), $\phi\pi^0$ background (dark shading), and the sum of $\phi\pi^0$, $\phi\eta$, and $D^+ \rightarrow \phi\pi^+\pi^0$ backgrounds (light); (b) $\cos\theta_{hel}$ distribution in the signal region, with the MC predictions: total (solid), total background (dark), and non- $\phi\pi^0$ background (light); (c) background-subtracted $\cos\theta_{hel}$ distribution and the MC prediction (histogram).

$D^0 \rightarrow K^+K^-$, where we have a signal of 21787 ± 226 events, and derive the branching fraction using the world average $\mathcal{B}(D^0 \rightarrow K^+K^-) = (4.12 \pm 0.14) \times 10^{-3}$ [10]. Many of the systematic errors associated with tracking and particle ID are at least partially canceled in the ratio.

The reconstruction efficiencies are estimated via MC simulation. Some differences in efficiency between data and MC have been noted, in particular for photon and π^0 reconstruction. For π^0 , this is studied using the double ratio of two modes of the η ,

$$\frac{\varepsilon_{data}(2\pi^0)}{\varepsilon_{MC}(2\pi^0)} = \frac{N_{data}(\eta \rightarrow 3\pi^0)/N_{MC}(\eta \rightarrow 3\pi^0)}{N_{data}(\eta \rightarrow \gamma\gamma)/N_{MC}(\eta \rightarrow \gamma\gamma)},$$

where $R_\varepsilon(\pi^0 \rightarrow \gamma\gamma)|_{\eta \rightarrow 3\pi^0} = R_\varepsilon(\eta \rightarrow \gamma\gamma)$ ($R_\varepsilon \equiv \varepsilon_{data}/\varepsilon_{MC}$) is assumed. The efficiency correction factors estimated from this study are found to be $(97.9 \pm 2.7)\%$ for π^0 ($E_\gamma > 50$ MeV and $P_{\pi^0} > 750$ MeV/ c), $(96.2 \pm 1.6)\%$ for η ($E_\gamma > 50$ MeV and $P_\eta > 500$ MeV/ c) and $(98.5 \pm 1.9)\%$ for a signal γ with $E_\gamma > 450$ MeV (assuming $\varepsilon_{\pi^0} = \varepsilon_\gamma \times \varepsilon_\gamma$). The overall detection efficiencies are summarized in Table I. The π^0 veto results in a low reconstruction efficiency for the $\phi\eta$ mode. The branching fractions for the observed D^0 decays and their ratios to the reference mode are summarized in the Table III.

TABLE I: Efficiencies for reconstructed modes [%]

| Mode ($D^0 \rightarrow$) | K^+K^- | $\phi\pi^0$ | $\phi\eta$ | $\phi\gamma$ |
|------------------------------------------------------|-----------|-------------|------------|--------------|
| Reconstruction | 10.4 | 6.48 | 2.22 | 4.32 |
| | ± 0.1 | ± 0.04 | ± 0.05 | ± 0.04 |
| $\mathcal{B}(\phi \rightarrow K^+K^-)$ | — | 49.20 | 49.20 | 49.20 |
| $\mathcal{B}(\pi^0/\eta \rightarrow 2\gamma)$ | — | 98.80 | 39.43 | — |
| Efficiency correction for $\pi^0 / \eta / \gamma$ | — | 97.90 | 96.20 | 98.50 |
| Total | 10.40 | 3.08 | 0.413 | 2.09 |

TABLE II: Estimated fractional systematic errors [%]

| | $D^0 \rightarrow \phi\pi^0$ | $D^0 \rightarrow \phi\eta$ | $D^0 \rightarrow \phi\gamma$ |
|--------------------------------------------------|-----------------------------|----------------------------|------------------------------|
| Tracking etc. | 0.59 | 0.59 | 0.59 |
| Particle ID | 2.74 | 2.74 | 2.74 |
| ΔM | 0.98 | 0.98 | 0.98 |
| Mass of ϕ | 0.94 | 0.94 | 0.94 |
| Efficiency correction for $\pi^0/\eta/\gamma$ | 2.75 | 1.62 | 1.94 |
| Fitting & BG | 1.67 | 2.01 | +2.46/-3.99 |
| $\mathcal{B}(D^0 \rightarrow K^+K^-)$ | 3.40 | 3.40 | 3.40 |
| $\mathcal{B}(\phi \rightarrow K^+K^-)$ | 1.42 | 1.42 | 1.42 |
| $\mathcal{B}(\pi^0/\eta \rightarrow 2\gamma)$ | 0.03 | 0.66 | — |
| MC statistics | 0.99 | 2.76 | 1.11 |
| Total | 5.88 | 6.16 | +5.86/-6.65 |

TABLE III: Measured branching ratios $\mathcal{B}_f/\mathcal{B}_{K^+K^-}$ for D^0 decay modes (f) and branching fractions $\mathcal{B}_f = (\mathcal{B}_f/\mathcal{B}_{K^+K^-}) \times \mathcal{B}_{K^+K^-}$. The first error is statistical and the second is systematic.

| Mode | $\mathcal{B}_f/\mathcal{B}_{K^+K^-}$ | $\mathcal{B}_f (\times 10^{-4})$ |
|--------------|---------------------------------------------------|---------------------------------------------------|
| $\phi\gamma$ | $[6.31^{+1.70+0.30}_{-1.48-0.36}] \times 10^{-3}$ | $[2.60^{+0.70+0.15}_{-0.61-0.17}] \times 10^{-1}$ |
| $\phi\pi^0$ | $[1.94 \pm 0.06 \pm 0.09] \times 10^{-1}$ | $8.01 \pm 0.26 \pm 0.47$ |
| $\phi\eta$ | $[3.59 \pm 1.14 \pm 0.18] \times 10^{-2}$ | $1.48 \pm 0.47 \pm 0.09$ |

The systematic uncertainties are summarized in Table II. The errors derived from the fitting process are estimated by varying the fit range, signal shape, and bin width in the fits; errors due to the backgrounds are estimated by varying background contributions within their uncertainties. The uncertainty in the acceptance due to the requirement on $M_{K^+K^-}$ for ϕ candidates is estimated by observing changes in the ratio $R_{D^0 \rightarrow \phi\pi^0} \equiv [N_{data}/N_{MC}]_{D^0 \rightarrow \phi\pi^0}$ while shifting the signal region by $\pm 1 \text{ MeV}/c^2$. Other systematic errors are estimated by observing changes to the double ratio, $R_{D^0 \rightarrow \phi\pi^0}/R_{D^0 \rightarrow K^+K^-}$. The error due to the uncertainty in the tracking efficiency is estimated by changing the maximum impact parameter criteria from 0.5 cm to 0.3 cm for $|dr|$ and from 1.5 cm to 1.0 cm for $|dz|$. Similarly, the errors due to particle ID and the $D^* - D^0$ mass difference are estimated by loosening the likelihood ratio cut to $\mathcal{R} > 0.5$ ($\mathcal{R} < 0.5$) for kaon (pion) selection and by shifting the ΔM window by $1 \text{ MeV}/c^2$ on each side. Due to the difference in the K^\pm momentum distribution between the $D^0 \rightarrow \phi\pi^0$ and $D^0 \rightarrow K^+K^-$ modes, the uncertainty on the particle ID efficiency does not exactly cancel in the ratio. The uncertainties in the branching fractions of submodes are taken from the current world averages [10].

To summarize, we have observed for the first time a radiative decay of the D meson, in the mode $D^0 \rightarrow \phi\gamma$. We also observe two other rare decays, $D^0 \rightarrow \phi\pi^0$ and $\phi\eta$, which are Cabibbo-suppressed and color-suppressed modes and constitute backgrounds for the radiative mode. The radiative $D \rightarrow V\gamma$ decays are expected to be dominated by long-distance contributions; however, the theoretical uncertainty on the rate is very large. The observed rate of $D^0 \rightarrow \phi\gamma$ constitutes evidence for significant long-distance contributions, and it provides an anchor for the further development of non-perturbative QCD.

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